A REVIEW OF THE COMMON CAUSES OF BOILER FAILURE IN THE SUGAR INDUSTRY

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Abstract

Unscheduled boiler outages in process industries are a major problem resulting not only in expensive emergency repairs, but also loss of production. This paper draws on the experience of the author's company relating to common failures of pressure parts of boilers. The paper identifies the most common types of pressure part failure and the metallurgical mechanism involved. With a knowledge of the underlying failure mechanism a number of basic causes can be identified. The paper suggests solutions that, if implemented, can reduce the incidence of unscheduled outages and thereby improve profitability.

Keywords: fatigue, pressure parts, wear

Introduction

Part of the function of the metallurgical section of Alstom Power – John Thompson Boiler Division is to conduct metallurgical inspections and failure analyses on all types and makes of boilers and prepare detailed inspection reports. This exercise is done on both sugar and non-sugar boilers in the sub-Saharan region. A review of the reports that have been produced over the past four years has shown that certain distinct categories of failures appear to be emerging. It was felt that sufficient data had been obtained to enable a statistical analysis of this information to be undertaken to see that if indeed a pattern or trend existed.

Unfortunately no centralised source of boiler statistics is available in South Africa therefore we were forced to examine data based solely on investigations carried out by ourselves. From market experience it is believed however that the figures presented are reasonably representative of the general situation in sub-Saharan Africa for the specific classes of boiler investigated. The study encompassed both fire-tube and water-tube boilers with a further subdivision of water tube boilers into sugar and non-sugar boilers.

Although there are only a limited number of fire-tube boilers in use in the sugar industry it was felt that seriousness of the failure mechanisms warrants their inclusion in this paper.

The statistics

The statistics encompass a wide range of boiler inspection and failure analysis reports from all over sub-Saharan Africa.

The fire-tube boilers covered a steam production range of 1-20 t/hr at pressures from 10 to 20 bar. Fuels include heavy fuel oil (HFO), Sasol gas, paraffin and coal. The survey covers a total of 85 fire-tube boilers inspected over a four year period (1998-2001).

The water tube boilers included in the analysis are mainly in the 35-200 t/hr range and usually operate around 30-40 bar. Some low-pressure units (13 bar) are included as are higher pressure 70 bar boilers from the utilities and paper industry. This section is sub divided into sugar industry and 'others'. 'Others' encompass examples from the utilities, petrochemical, food processing, and paper industries. The sugar boilers obviously fire bagasse often with coal or HFO as a secondary fuel. The 'others' fire various fuels including coal, HFO and wood. The time frame of the latter study is four years (1998-2001) with a total of 48 boilers.

The results are presented in two tables. Table 1 gives the *attributed mechanism* of the failures. Table 2 presents what is felt to be the *operational causes* of failures.

Failure mechanisms

The failure 'mechanisms' were, more or less, self-selective.

Table 1. Mechanisms of pressure part failures.

Mechanism	Package boilers		Water-tube boilers (WTB)		WTB-sugar		WTB-other	
	No.	%	No.	%	No.	%	No.	%
Corrosion/Erosion	9	11	11	23	5	22	6	24
Corrosion fatigue	23	27	5	10.5	1	4	4	16
Thermal fatigue	38	45	3	6	1	4	2	8
Mechanical fatigue	7	8	5	10.5	2	9	3	12
SCC	0	0	2	4	1	4.	1	4
Overheating	5	6	21	44	12	53	9	36
Other	3	4	1	2	1	4	0	0

Fatigue
Fatigue accounts for 80% of the failures investigated in fire tube boilers and 28% in water tube boilers. Significantly in the non-sugar, watertube section this rises to 36% but drops to 17% for sugar boilers. However despite its low incidence in the sugar industry, it is worth a close look at the problem particularly in the light of future industry trends and potential risk.

As fatigue is such an important feature and the various mechanisms are quite distinct, it has been split into the three most common types, namely Thermal, Corrosion and Mechanical Fatigue. From experience it is known that thermal and corrosion fatigue are common occurrences, particularly with fire-tube boilers.

Thermal fatigue
Thermal fatigue is defined as fracture resulting from the presence of temperature gradients that vary with time in such a manner as to produce cyclic stresses in the structure (ASM Handbook, Vol.11, 1986, p11).

Thermal fatigue is particularly prevalent in package boilers especially those with high heat transfer zones as reported by Kohan and Spring (1991). It is most often seen as cracking of the tube ends (formerly called fire cracking). If left unrepaired, the crack will run into and through the ligaments resulting in costly replacement of the tube sheet. The ends of the furnace tube/flue can also suffer from thermal fatigue in a similar manner.

Thermal fatigue occurs when metal is subjected to a number of rapid heating and cooling cycles causing large differences in thermal expansion between the structural members. Depending on the magnitude of the thermal shock involved, failure can occur with less than ten cycles. The material in question is normally in a condition of high restraint. Biaxial or triaxial stresses are induced in the affected surface producing microcracks on the surface of the material. Once initiated the crack will continue to propagate with each cycle. In fire tube boilers the most common cause is internal scale, which prevents sufficient heat transfer and hence adequate cooling. Over-firing, incorrect burner settings and too many on/off cycles are amongst common causes resulting in cracking.
In water tube boilers thermal fatigue can occur when there is frequent wetting of a hot surface such as is caused by an ill placed and leaking valve dripping internally into a hot steam line. Such failure of a steam line could have very serious consequences.

Thermal fatigue cracks can be similar to corrosion fatigue and the two are often confused. Thermal fatigue can only be eliminated by removing the offending thermal cycling.

Corrosion fatigue
Corrosion fatigue is defined as cracking produced under the combined action of fluctuating stress and a corrosive environment at lower stress levels or frequencies than would be required in the absence of a corrosive environment. (ASM Handbook, Vol.11, 1986, p 2).

Corrosion fatigue in boilers is extremely dangerous and is the subject of many treatises. It requires the interaction of cyclic loading, corrosive environment and a high residual stress field. Several failures have resulted in considerable loss of life. As with thermal fatigue it manifests itself in quite different forms in fire-tube and water-tube boilers. From Table 1 it can be seen to be the second most common cause of failure in the sample of fire tube boilers. As reported by Yates (1999) somewhere between 8% and 12% of fire tube boilers in the UK have been found to be affected. The reverse fillet welds of the main tube to shell and furnace tube to tube sheet are the most common places of attack in fire tube boilers and the problem is often described as toe cracking.

Failure is initiated at the surface in a high stress area. A weld undercut, corrosion pit or other defect, usually at the toe of the weld, could cause the high stress. The joint area is usually in high restraint. The first phase of the initiation is the cracking of the protective oxide layer by the cyclic loading. This permits fresh attack by the corrosive medium on the bare metal and the formation of micro-cracks. The exposed metal at the root of the crack is oxidised and then cracks at the next cycle so propagating the failure. Cracks are distinctively wedge shaped and transgranular particularly in the early stages.

Most of the water tube boilers that were found to exhibit corrosion fatigue were in the higher pressure range. The appearance of these defects is typical of corrosion fatigue but there may also have been a contribution from caustic embrittlement, also known as stress corrosion cracking (SCC). In the sugar industry the problem is not common in sub-Saharan Africa and this may be due to the lower operating pressure. From the paper by Starr (2001) it is clear that cyclic loading of high pressure units through on/off cycles is leading to and increased incidence of failures such as corrosion fatigue on power boilers. Corrosion fatigue has been observed in the drums of several 70 bar boilers in the region and it is a reasonable conclusion that the trend toward higher pressure co-generation boilers will increase the frequency of occurrence of this problem. The defect will occur where there is a high number of on/off cycles and corrosion has been allowed to develop. Stop/start cycles are of course the most damaging part of boiler operation. The favoured area of nucleation is in tube holes of drums where there has been an ingress of boiler water often of high pH. In high pressure units tubes are often welded to the drum which creates a high residual stress field. Rapid stops and starts have been known to stress these joints through rapid expansion or contraction resulting in the welds cracking. This allows water ingress to the tube hole area contributing the corrosion factor to the cracking problem.

An example of corrosion fatigue failure is shown in Figure 2.

Figure 2. Corrosion fatigue in a steam drum.

These cracks initiated after a 'quick fix' weld repair of a cracked ligament during the crop season. This introduced the high stress factor. Seepage of boiler water and cyclic loading did the rest. They had propagated over a period of 16 years. The cracks were discovered during and inspection prior to re-engineering the boiler to operate at a higher pressure. Had they been allowed to propagate into rupture the explosion would have destroyed the boiler house. The rectification involved the fitting of a replacement section (window) into steam drum.

Mechanical fatigue
Mechanical fatigue can be defined as fracture under fluctuating mechanical stresses having a maximum value less than the ultimate tensile strength of the material (ASM Handbook, Vol.11, 1986, p 4).

Mechanical fatigue is what most people imagine when the word 'fatigue' is mentioned. Several instances in water tube boilers have been encountered where cracking has occurred in the tube to manifold weld of drainable superheaters. This was due to the vibration from inadequately supported elements. This is an often-neglected part of boiler maintenance. Other failures, again from vibration, have been due to defective tube-to-tube welds a result of manufacturing defects.

Corrosion and erosion
Erosion and corrosion have been grouped together as material wastage and this is perhaps unfortunate, as the two mechanisms are quite distinct. In fire tube boilers, corrosion is the primary mechanism and in most cases this can be attributed to either poor water treatment (usually low pH) or inadequate long-term storage. This can lead to serious under deposit corrosion often requiring the replacement of a section of the boiler shell. However cases involving inadequate blow down have been observed where a deposit was allowed to build up in an area of low circulation. The result was serious internal corrosion of the shell plate Over-firing producing ‘Departure from Nucleate Boiling’ (DNB) with resultant water side pitting has also been observed.

Inadequate maintenance of valves and fittings can result in joint leakage leading to external under lagging corrosion.

In water tube boilers erosion and corrosion take many forms with sand erosion almost being accepted as a necessary evil in the sugar industry. In three-pass boilers material wastage of the main generating bank can be a major problem as has been previously reported (Moor, 1985). The use of a main bank gap will reduce but not eliminate the tube erosion around the end of the baffles. It can however be further minimised by the selective fitting and maintenance of shrouds in critical areas. Many erosion problems result from holes and gaps in baffle walls as well as the failure to maintain the shrouds in a serviceable condition. As such many of the problem in these cases can be attributed to poor maintenance. Modern 'Non-destructive Examination' (NDE) makes the examination of main-banks and the monitoring of erosion patterns much more practical. Main bank tube erosion is much less severe in modern single pass boilers.

Corrosion occurs externally where damp conditions are allowed to remain over the off-crop. A galvanic cell will develop in the warm moist environment with rapid material wastage Repair can be very expensive. Typical locations are wall tubes and mud drums. Figure 1 schematically shows the corrosion that occurs on the mud drum by allowing the sand to build up and leaving it wet during the off crop (washing down the main bank). A galvanic cell is set up with preferential wastage normally occurring on the drum. One particular boiler which was operating below 29.5 bar design pressure lost two millimetres of material (as shown in Figure 1) on the major ligament. Major drum repairs had to be undertaken to bring the boiler back to design thickness and permit it to operate at its original pressure (31 bar). In some cases, depending on the steel grades involved, the tube will corrode preferentially at the interface. It is extremely difficult to detect this corrosion even using NDE techniques. Therefore it is infinitely easier to prevent it in the first place.

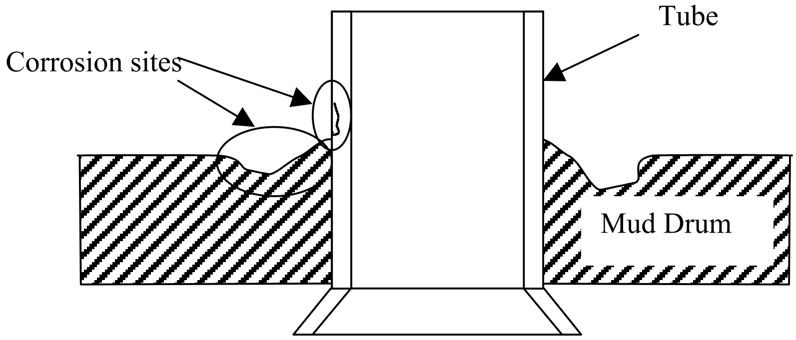

Figure 1. Wastage around a tube hole in a mud drum.

Internal wastage due to active oxygen corrosion will occur in drums, tubes and manifolds if lay up practices are inadequate during the off crop.

Stress Corrosion Cracking (SCC)

Stress Corrosion Cracking (SCC) is a cracking process that that requires the simultaneous action of a corrodent and sustained tensile stress. (ASM Handbook, Vol.11, 1986, p10) In relation to boilers and this paper this problem was formerly called caustic embrittlement.

Stress corrosion cracking is often confused with corrosion fatigue and has been observed in both the steam and mud drums of boilers. If there is seepage between the tube and drum it is possible for the concentration of NaOH to increase dramatically in this area. Metallurgically, the drum under load is in tensile loading and with a high localised caustic concentration, the ideal environment is produced for SCC. Although the incidence of SCC was found to be low it is known that there were several major problem in 70bar petrochemical boilers. To prevent SCC in the best way is to prevent the concentration of corrosion compounds either mechanically or chemically through appropriate maintenance and water treatment respectively.

Overheating

Overheating encompasses furnace tube collapse in fire tube and both short and long term overheating of tubes in watertube units. Any forms of metallurgical degradation such as creep graphitisation or spheroidisation are included in this section.

Overheating is the biggest mechanism indicated in Table 1. In fire tube boilers it would normally manifest itself as collapsed furnace tubes or bulged reversal chamber walls. In watertube boilers it is usually tubes that are affected. These can be in the furnace, roof, superheater or main bank areas.

The tube failure is normally divided into two types.

- Short term characterised by a thin edge fish-mouth rupture.
- Long term characterised by swelling and a course outer tube texture.

Short term overheating often occurs after start up and may be attributed to blockages in the tube such as scale or cooldrink cans (left in manifolds or drums during maintenance). A low water level could also produce sudden rupture. There is not usually any metallurgical damage to the surrounding steel microstructure and the edge of the rupture is very thin with a large amount of deformation clearly having taken place. The underlying cause of short term overheating is the lack of sufficient cooling on the internal surface of a tube. As steel temperature increases so the yield point (the point at which it changes to plastic deformation) decreases. The lack of cooling will produce material temperatures, which are so high, that the steel will not be able to contain the internal pressure and will deform in a plastic manner. The temperatures involved are anything in excess of 450°C. The ruptures are usually fairly dramatic in appearance.

Air/water locks in superheaters that prevent the flow of steam to cool the tube are another common cause of short term overheating.

Long term overheating on the other hand, as the name implies, takes place over a prolonged period. It is the more common type and most often occurs in furnace walls, screen tubes, roof tubes and superheaters. As the tube is forced to operate at a temperature above that at which it was designed, the microstructure starts to degrade. Boiler tubing consists of a matrix of soft ferrite grains interspersed with islands of pearlite. Pearlite is a laminated structure of hard iron carbide (Fe_3C) and soft ferrite. It is the manipulation of these the ferrite and pearlite phases that give steel its unique range of properties Unfortunately as the temperature increases the shape of the iron carbide becomes unstable and wants to reach a more stable condition. It can do this in two ways. Either be breaking down into Iron and Carbon (graphitising) or forming iron carbide spheroids (spheroidisation). The operating temperature will determine which degradation takes place but it must be above 450°C. This temperature can be increased by the addition of various elements such as Chromium and Molybdenum. Graphitising occurs at a lower temperature than spheroidising. The mechanisms are solely time and temperature dependent. Creep is often classed as long term overheating but it also involves the application of load as well as temperature and time. It results in the formation of grain boundary voids.

The ultimate fate of the tube is swelling followed by the formation of grain boundary cracks at the surface indicated by a tree bark affect on the outer surface. This precedes rupture. A grading system is used to classify the degree of degradation which can only be assessed by metallographic examination.

Long term overheating is the most common of the failures investigated and could be symptomatic of one of many things such as poor circulation, scaling, flame impingement, etc. Swelling in itself does not imply pending failure but it does warrant immediate investigation to establish the nature and causes of the metallurgical damage. The process is not reversible but it can be halted.

One notable case of swelling was the unrecorded and presumed unofficial welding of refractory supports to furnace tubes. Some years later after the removal of the support the affected tubes exhibited swelling at the same height. As no records of the welding were available it was thought to be due to overheating. Metallurgical investigation 'discovered' the welding and indicated that no major degradation had occurred. As far as is known the boiler continues to operate successfully.

Other
'Other' covers miscellaneous defects and includes manufacturing and shipping problems. Other failure mechanisms were due to miscellaneous problems, including manufacturing or construction defects and laminations in very old boiler plant.

Hydrogen damage is defined as a general term for embrittlement, cracking or blistering and hydride formation which can occur when hydrogen is present in some metals (ASM Handbook, Vol. II, 1986, p 10). It was expected but no incidences were found in the examples reviewed. These inspected units were mainly lower pressure units, whereas boilers operating above 69bar are more susceptible to hydrogen attack (Port and Herro,1991).

Similarly no incidences of *caustic attack* were observed.

Table 1 showed that thermal and corrosion fatigue were the major causes of failures in the pressure envelope of firetube boilers but were of less significance in watertube units. (It must be appreciated the results of failure could nevertheless be more catastrophic in a watertube boiler.)

However with regard to the sugar industry the most common mechanism was found to be overheating followed by corrosion /erosion, something that was mirrored in failures in water-tube boilers as a whole.

Where more than one mechanism was found the failure was attributed to that which was responsible for the initiation.

Causes of failures

Table 2 divides causes of boiler failure into four simplified groups. The number occurrences of each type of failure per class of boiler is then given.

Causes were selected such that they could easily be appreciated. To keep it as simple as possible the number of categories was kept as few as possible. Failures were allocated to categories as part of the failure analysis. It is worth restating that the statistics were drawn from failure analysis data which, by definition, indicates a problem in the boiler operation. As such, the results may not be surprising.

In the simplest of terms they have been reduced to four categories:

- inadequate water management
- bad operation
- poor maintenance
- ‘other’ factors (outside management's direct control, such as manufacturing defects, transport damage, etc.).

Table 2. Causes of boiler pressure part failures.

Cause	Package boilers		Water-tube boilers (WTB)		WTB- sugar		WTB- other	
	No.	%	No.	%	No.	%	No.	%
Water treatment	26	31	8	17	3	13	5	20
Mal-operation	44	52	28	58	13	57	15	60
Maintenance	9	12	8	17	4	17	4	16
Other	6	7	4	8	3	13	1	4

Again it must be emphasised that the figures presented and discussed below are based solely on investigations that the author's organisation has undertaken and the conclusions reached in the investigation reports. They embrace all makes of relevant boilers in use in sub-Saharan Africa.

From Table 1, it can be seen that the proportion of each mechanism has significant variations between firetube and watertube boilers, and this reflects in different causes of failures.

Looking at the failures with firetube boilers, mal-operation and water treatment account for the bulk of attributable causes.

In watertube boilers the most common cause of failure in the figures examined was mal-operation, followed by water treatment with maintenance on a par. In the sugar industry watertube boilers, mal-operation was again found to be the biggest problem, followed by maintenance and then water treatment.

The 'other' covers problems perceived as being outside mill management control e.g. manufacturing defects.

Water treatment

Water treatment is a major problem in firetube boilers mainly because of the generally poor standard of operation. The dangers of inadequate water treatment are spelled out in many sources such as BS 2486 Recommendations for the Treatment of Water for Land boilers; BS2790 Specification for the Design and Manufacture of Shell Boilers, to name but two. However, many boiler users are very small operations, such as laundries etc. and senior management often do not understand fully the importance of a properly managed water supply system.

In water tube boilers the level of professionalism is usually much higher and usually there is a qualified chief engineer. Nevertheless, the situation still arises where untreated feed water is still being used either from rivers or boreholes in many sugar mills in the more remote areas of Africa. This may be due to financial reason or shear logistics. Hence this cause being number three on the list. The inevitable result in the boilers in question is scaling of the tubes and impedance of heat transfer. In water tube boilers this most often results in long-term ruptures of main generating bank or furnace wall tubes.

Mal-operation

Mal-operation was found to be the number one cause of boiler outages and is always a bitter pill to have to swallow. It is interesting that the percentage varies little between firetube, sugar and ‘others’ and that, in itself, is significant.

In fire-tube boilers, mal-operation would include overfiring, rapid start-ups, excessive pressure swings, poor blow-down practices, too many ‘on/off’ cycles with gas or oil burners.

In water tube boilers a major factor was found to be the start up procedure. This is reflected in the high incidence of overheating (53% in sugar boiler failures). Starting from cold is a most critical point in a boiler operation cycle. If superheaters have not been drained properly then a steam lock can form during start up causing tube overheats. Failure to regulate bagasse flow properly can produce puffing and/or hot spots in the boiler. Similarly if coal spreaders are not set up correctly local hot spots can develop. Local hot spots can lead to either short or long term overheating. Incorrectly adjusted oil burners can cause flame impingement.

Sugar slug ingress or carryover causes problems in drums and superheaters. This would be classed as an operator problem.

Maintenance
Maintenance or more correctly inadequate maintenance was seen to be the cause of several failures. Examples are major tube corrosion underneath the lagging and cladding. Another example is the unqualified seal welding of tubes to the steam drum with resultant cracking of the drum.

'Other'
'Other' includes some mechanical fatigue of staybars in firetube boilers resulting from prolonged transport by road. It is believed that in one case the tubes were of such a length they went into resonance, cracked and leaked on start up. Another failure in this category was boiler shell damage due to falling of a truck. Finally a superheater weld failed in mechanical fatigue due to a poorly executed factory weld, after 15 months in service. Clearly all such failures are outside the responsibility of mill management.

Preventative measures

As always the best solution to the problem is prevention. The statistics as indicated above show the following in relation to the sugar industry.

Mal-operation 57%
This is highlighted as the most pressing problem. Overheating is the most common mechanism and this in turn in most cases is a result of operating parameters. Load swings are inevitable but relevant personnel should be aware of the damage potential that they pose and place a high priority placed on their minimisation.

Situations in power boilers such as discussed by Starr (2001) are not going to go away. This type of loading of water tube boilers typifies the sugar industry. Much of the damage to tubing occurs during rapid start ups, even though the results may not manifest themselves for many months.

Water treatment 17%
From Table 2 it can be seen that in macro terms the main cause of failure is usually attributable to mal-operation or lack of proper water treatment. With the advent of more and more co-generation boilers in the industry, the aspect of water treatment has become more important. The use of raw feed water in most applications is obviously totally unacceptable.

Maintenance 17%
Corrosion and erosion are problems that can be minimised. Careful inspection during the off crop followed by corrective structural or refractory maintenance will reduce both problems. It is essential that baffles, shrouds and refractory should be kept in good condition. Build up of ash, sand or unburned bagasse creates a corrosive environment. The external panel walls should be inspected for corrosion particularly at the bottom. Any signs of damage to external cladding should be repaired after inspecting the underlying tube.

A significant number of failures have been identified where unauthorised welding has been carried out on tubes or drums. Tubes, drums, superheaters etc. are defined under the 'Vessels under Pressure Regulations' (1998) as pressure vessels. Weld repairs on such pressure vessels are clearly defined and subject to stringent controls. Carrying out unauthorised repairs is not only dangerous but also illegal and could result in imprisonment. All weld repairs on pressure vessels *must* be carried out by suitably qualified personnel to authorised procedure, pressure tested and duly recorded.

Other 8%
Manufacturers and contractors have a contribution to make through design and quality control.

Conclusion

Inspections have been undertaken in boilers up to sixty years old and some of these older units are in better condition than sixteen year-old plant inspected. Everything depends on management and its attitude. In some countries, where sugar mills had been nationalised, the boilers are relatively young but found to be completely worn out. This is not the fault of the chief engineer or the boiler staff, who invariably have been, and are, working miracles to keep the plant running. The problem usually lies with the executives who have starved the mill of funds for various reasons. Under such conditions preventative maintenance had been impossible and everything was run on a breakdown basis. Fortunately no major accidents occurred and with new initiatives many of these rundown mills are undergoing a rejuvenation.

A multi-pronged approach is therefore required involving corrective action, in the form of water treatment, and operating procedures in association with legislation and education. Awareness programmes are being conducted in Southern Africa to alert Competent Persons and users alike to the new problems that are arising. With regard to fire tube boilers we are seeing a positive result to education and operator training with a reduction in certain types of failure (notably thermal fatigue). It is to be hoped that similar re-education would produce similar results in the water tube sector.

New technology also permits closer monitoring of boiler operation using electronic controls and recording devices. In addition it gives boiler users real time access to boiler performance and control, in order to avoid or minimise the outages caused by the above mentioned failures.

REFERENCES

ASM Handbook, Vol 11 (1986). Failure Analysis and Prevention. American Society for Metals.

Kohan, A and Spring, M (1991). *Boiler Operator's Guide.* McGraw-Hill Inc, USA. pp 53-54.

Moor, B St C (1985). A reliable high efficiency sugar mill boiler. *Proc S Afr Sug Technol Ass* 59: 118.

Port, RD and Herro, HM (1991). *The Nalco Guide to Boiler Failure Analysis.* McGraw-Hill Inc, USA.

Starr, F (2001). Following the Load. Materials World April 2001. Institute of Materials.

Yates, M (1999) In-service examination of boilers. Seminar on Boilers in Europe. Institute of Mechanical Engineers, London.

Vessels Under Pressure Regulations (1998). Occupational Health and Safety Act 85 of 1993, pp 1701-1726.

British Standards Institute (1978). BS2486 Section 7(b)4 Recommendations for the treatment of water for land boilers. London, UK.

British Standards Institute (1978). BS2790 Specification for the design and manufacture of shell boilers of welded construction. London, UK.